FFAG Instrumentation and Commissioning

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OUTLINE

Instrumentation

Commissioning

Possible R&D

Summary

C-AD Machine Advisory Committee Meeting, Nov. 25-27, 2013

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Summary

Fill Pattern

hadron accelerator: $f_{rev} \sim 78$ kHz, $N_p^{max} = 120$

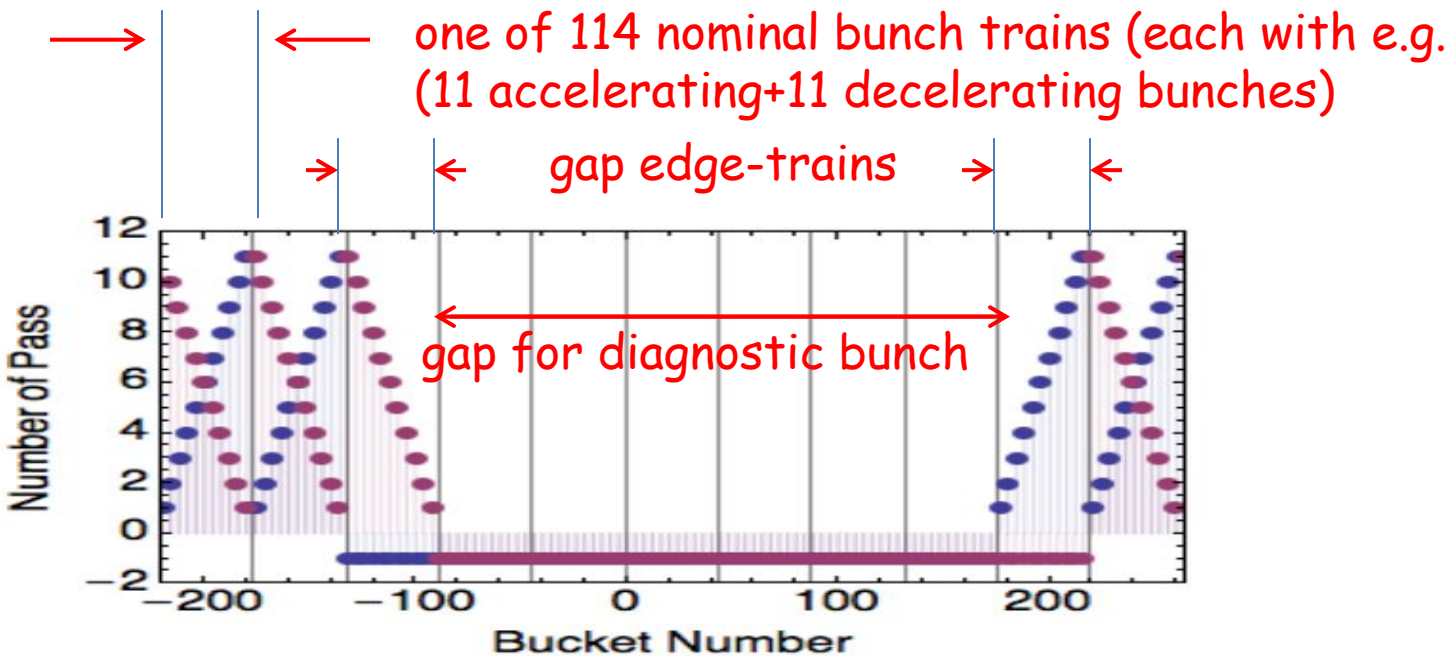
➡ f_p = proton bunch repetition frequency

$= N_p^{max} f_{rev} = 9.38$ MHz

FFAG accelerator: f_e = electron bunch repetition frequency = 9.38 MHz (for collisions) = train repetition frequency

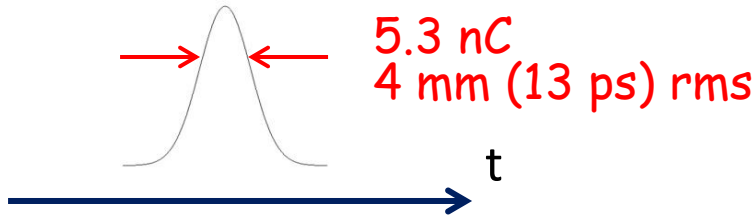
$f_{rf} = 412.8$ MHz

➡ maximum number of bunch trains = 120
of length = RHIC circumference/44 ~ 87 m or ~ 290 ns

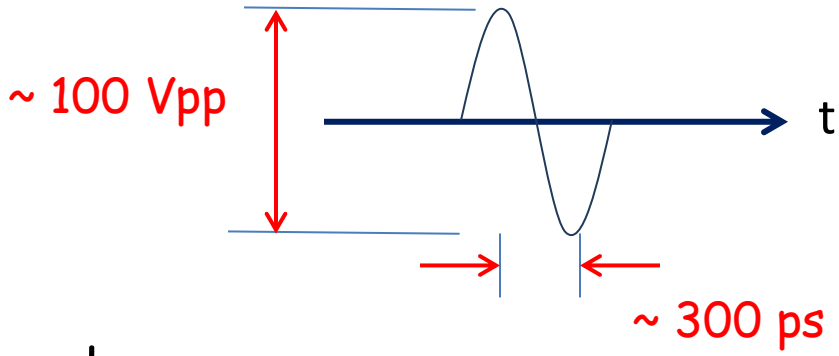


Beam Signals

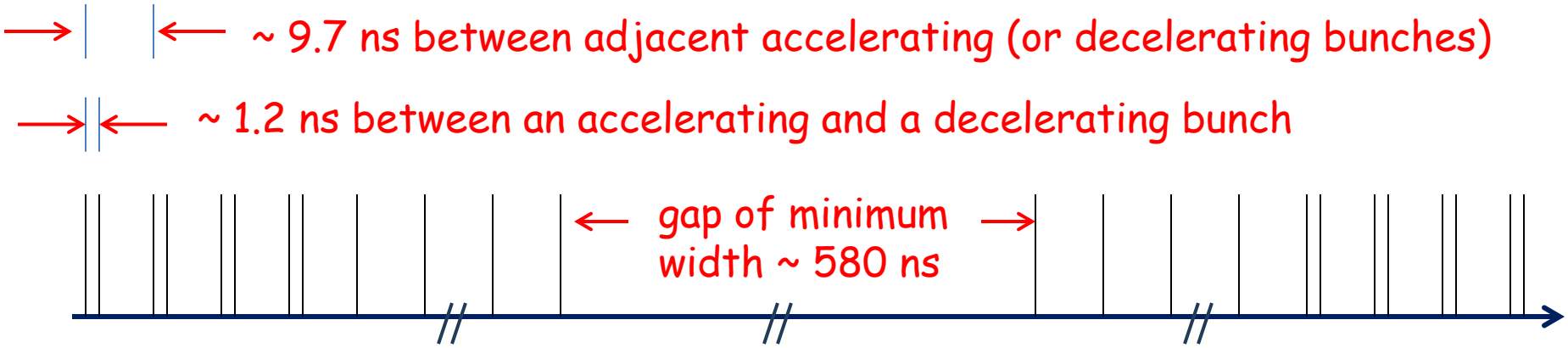
Charge distribution



BPM signal



Transformer signal



Diagnostics

<u>standard technologies with no developments required:</u>

- beam loss monitors (diodes, ionization chambers, PMTs, etc.)
- beam current monitors (transformers)
- bunch arrival time monitor (BPM relative to rf)

<u>standard technologies with FFAG adaptation aspects:</u>

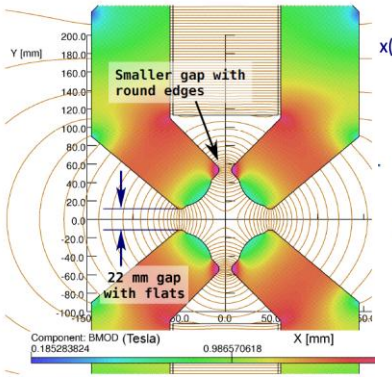
- beam position monitors

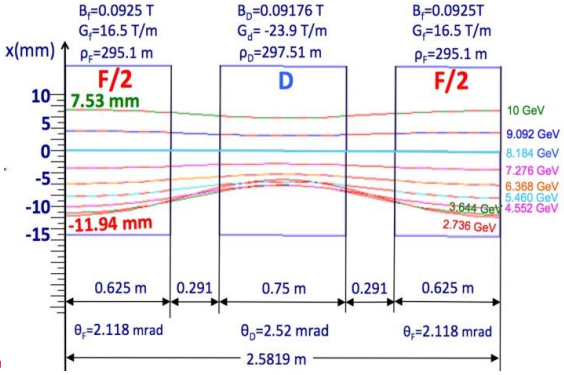
- beam imaging devices
  - transverse (scintillators, OTR/YAG, synchrotron radiation)
  - longitudinal (streak camera for bunch length, arrival time)

FFAG BPM

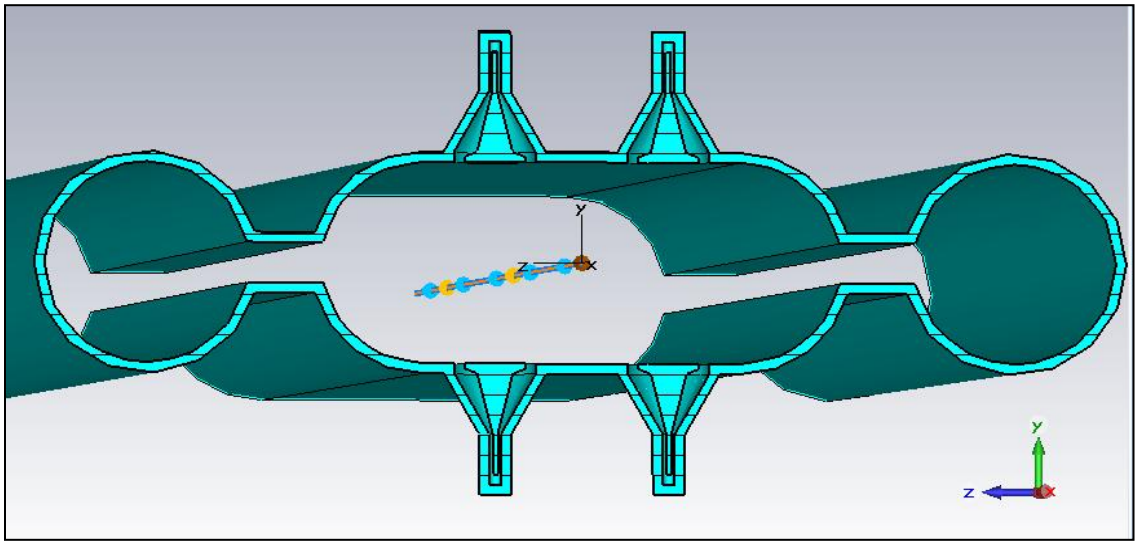
dimensions based on

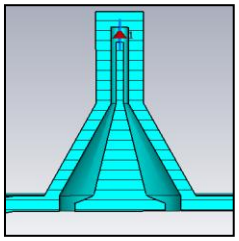
magnet design → full height ~ 22 mm
design orbits → full width ~ 30 mm





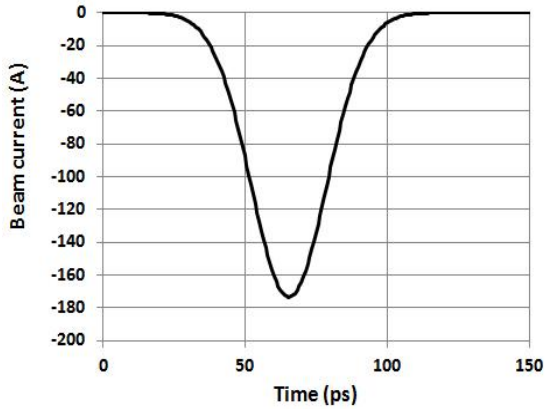
button geometry

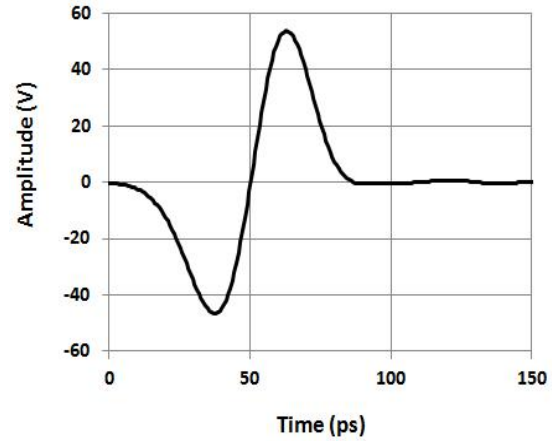


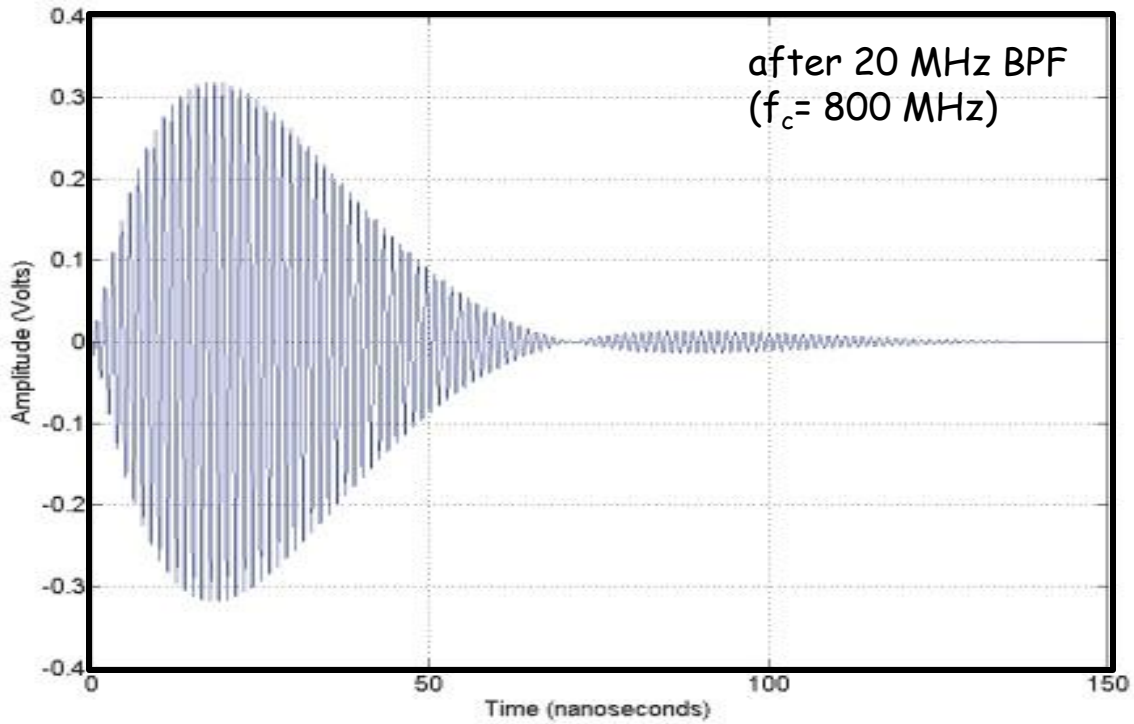


6 mm button radius
4 mm rms bunch length
3E10 electrons/bunch

Simulated BPM Bunch Signals

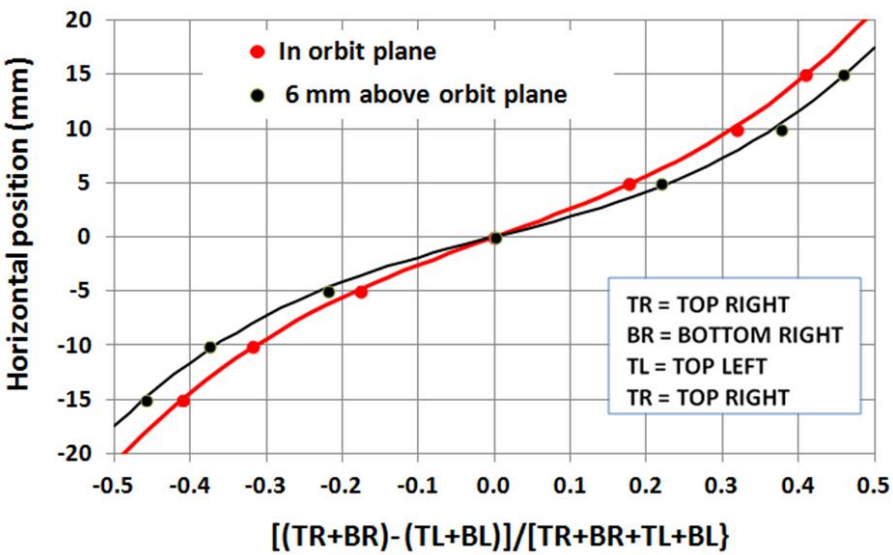


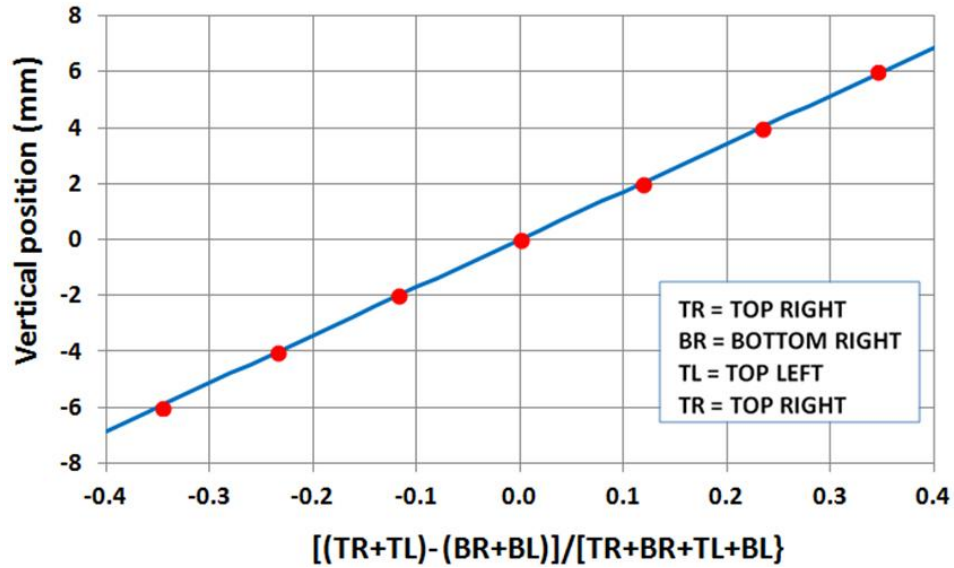




BPM Calibration

Results of coarse grid map with steps of 5 mm horizontally and 2 mm vertically (with total area: +/- 15 mm horizontally and +/- 8 mm vertically):





points: calculated from signals simulated with Particle Studio
lines: least squares fit with a cubic function

➡ one-to-one mapping of response will provide calibration for absolute beam positions (including for far off-axis beams)

Signal Processing

Consists of 3 parts:
(1) rf front end
(2) digitizer
(3) FPGA

Options for the latter 2, for example:

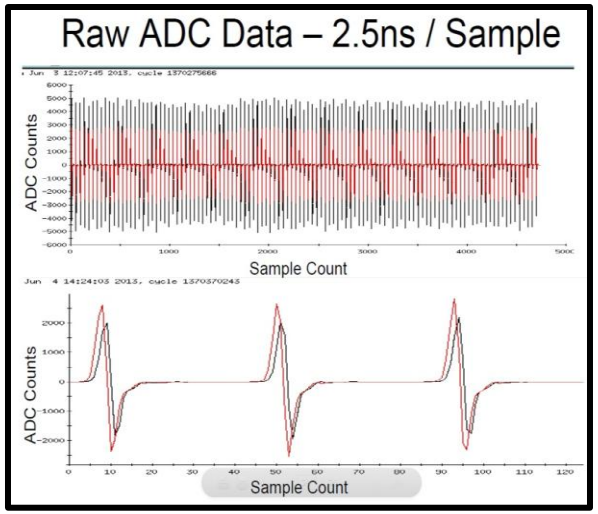
- off-the-shelf possible processor: e.g. Libera Brilliance Single Pass electronics (as used in ERL)

Performance specification

- Turn-by-turn resolution: < 0.5 µm typical value (0 dBm, ~ 300 kHz revolution frequency)
- Slow monitoring resolution: ~10 nm typical value(0 dBm, 10 S/s)
- Beam current dependence: 1 µm (0 dBm --> -50 dBm)

- developments for RHIC BPM upgrade

(Xilinx Zynq FPGA –based processing, here with 400 MSPS A/D converters)



BPM locations

<u>FFAG cells:</u> 1 BPM per 2 cells (4 magnets)

<u>spreaders and combiners:</u>

Each will have sets of3 BPMs (position, angle, energy) to ensure
- proper (on-axis) launch into linac / design trajectories into first FFAG cell
- proper energy before and after linac

Each will have a pair of BPMs just upstream and downstream

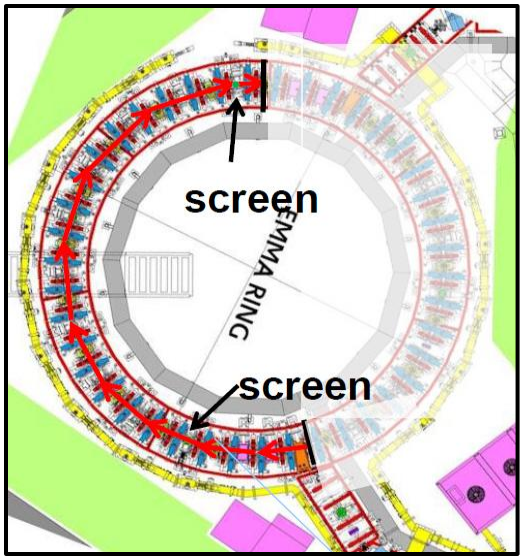
<u>linac</u>: single BPM between cavities as needed

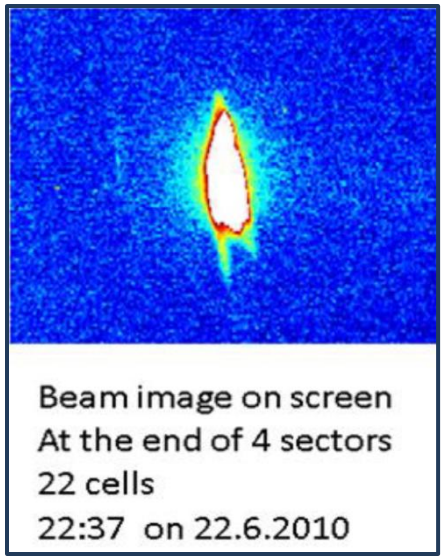
<u>straight sections</u>: BPM pairs as needed for given optics design

<u>detector bypass lines</u>: BPM pairs as needed for given optics design

Beam Imaging Devices

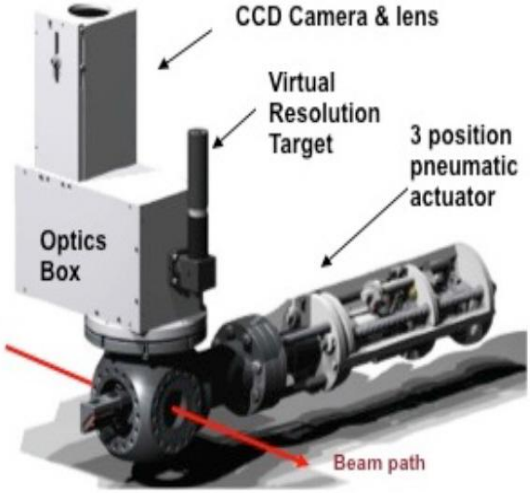
EMMA concept: YAG screens within FFAG cells,
position-dependent interception of different energy passes





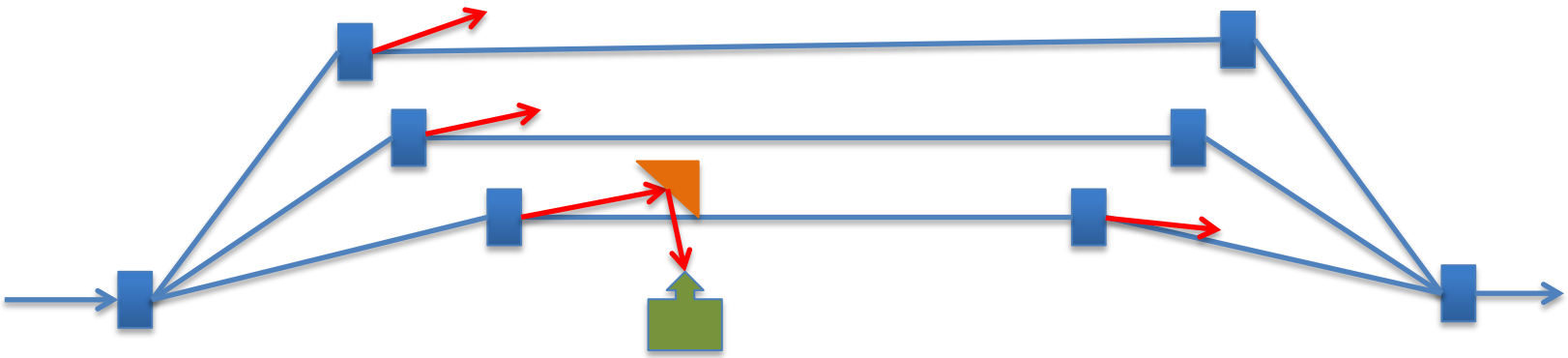
For the e-RHIC FFAG, instrument the separate beamlines of the spreaders and/or combiners with

- OTR screens for first-few turn, single-bunch imaging using for example BNL design for ERL (fabricated by Radiabeam) →



- synchrotron radiation

Synchrotron Radiation Monitors



Radiation will be extracted from the bending magnets of combiners/spreaders

Visible light will be reflected to the camera with water cooled mirror

The relevant parameters are in the table on the next slide assuming

ε = 20 mm-mrad (normalized rms emittance)
B_{dipole} = 1.35 T
β = 70 m
λ = 500 nm (wavelength of detected light) with 10% filter BW
1" diameter lens 5 meters away from source
image occupied: 10000 pixels
exposure time: 30 ms

E, GeV	λ_c, nm	dN/dΩ, ph/mrad^2/s	ψ, mrad	ph/pixel	ε, nm	σ, mm	Resolution, μ
2.7	0.184	5.1×10^9	2.6	2.0×10^5	3.73	1.62	192
3.6	0.104	3.3×10^9	2.4	1.2×10^5	2.80	1.40	211
4.6	0.067	2.3×10^9	2.2	7.6×10^4	2.24	1.25	228
5.5	0.046	1.7×10^9	2.1	5.4×10^4	1.87	1.14	242
6.4	0.034	1.3×10^9	2.0	4.0×10^4	1.60	1.06	255
7.3	0.026	1.1×10^9	1.9	3.1×10^4	1.40	0.99	266
8.2	0.021	9.0×10^8	1.8	2.4×10^4	1.25	0.93	277
9.1	0.017	7.6×10^8	1.7	2.0×10^4	1.12	0.89	287
10.0	0.014	6.5×10^8	1.7	1.6×10^4	1.02	0.84	296

➡ photon yield sufficient
resolution provides error in measured beam size below 10%

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FFAG Commissioning

Orbit and optics corrections were presented earlier by V. Litvinenko and C. Liu

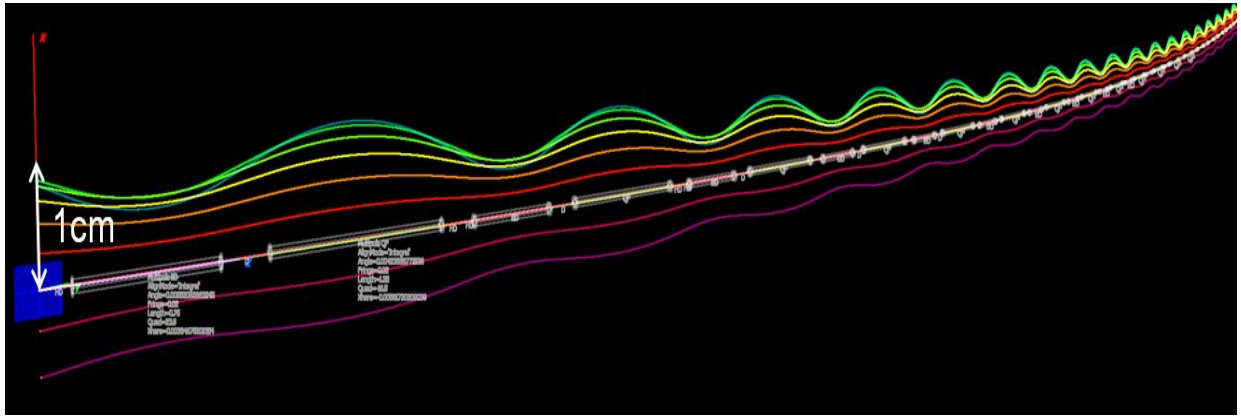
Commissioning will take place with a single, nominal-intensity bunch (5.3 nC)

first acceleration pass

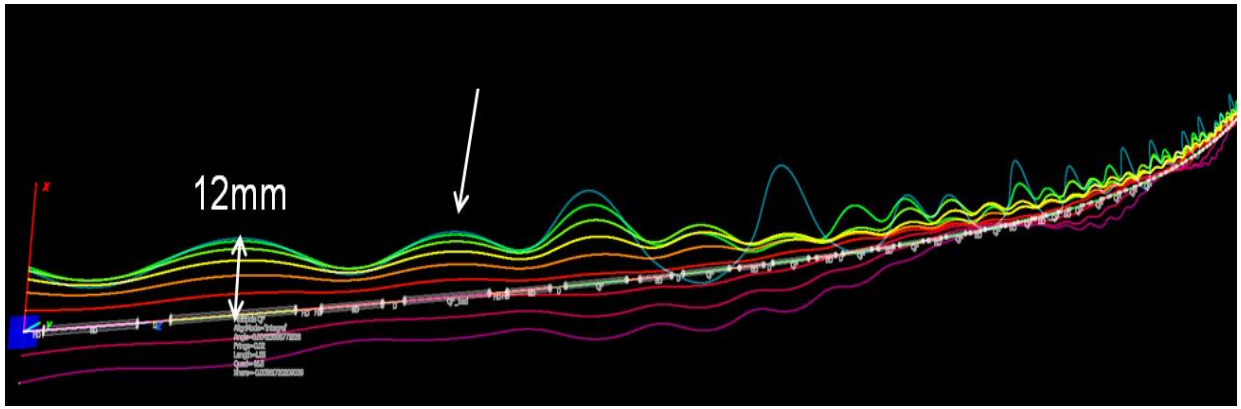
- inject into linac, using linac BPMs, adjust launch from injector
- set linac phase ϕ by maximizing $x(\phi)$ in spreader
- using design dispersion, verify and/or set energy gain, ΔE, where $E_0=\Delta E+E_{inj}$
- using spreader BPMs, adjust spreader correctors for proper launch into first FFAG cell
- circulate beam through one pass (ref. C. Liu's presentation)
  - if needed, using BPMs and loss monitors to localize errors, use SVD or "sliding bumps" to thread beam through regions
  - correct gradient errors
  - iterate if necessary

effect of egregious errors (S. Brooks)

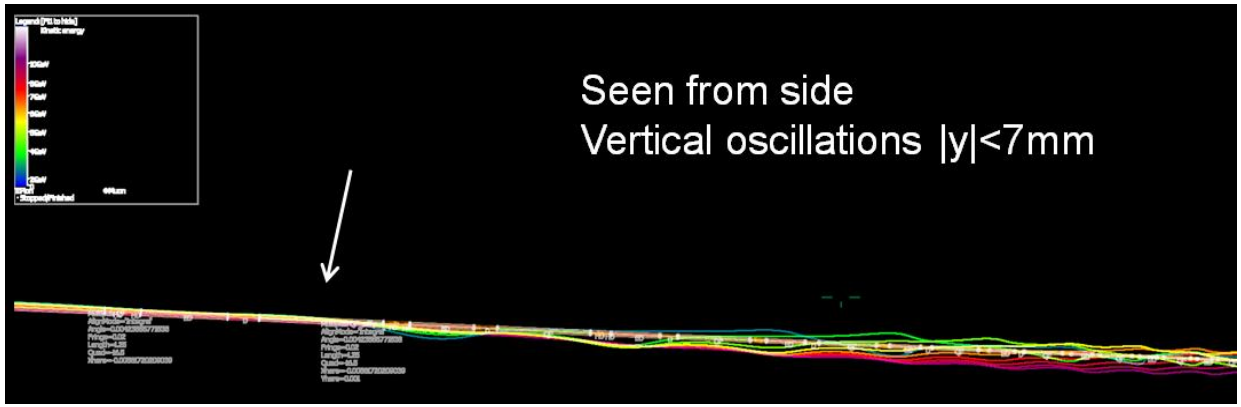
lattice with no errors



20% decrease in single QF



1 mm vertical shift in QF position



➡ beam still circulates in all cases

first acceleration pass, continued

- adjust voltage on energy-compensating cavity to restore beam energy at start of linac (assuming design dispersion in combiner)
- using available other BPMs and design dispersion, measure energy (if inconsistent with above, use this as energy E_0, set ΔE, measure dispersion η in spreader: $\eta = dx/d\delta$, $\delta = E-E_0/E_0$

generic acceleration pass (1 low-to-high energy ring transfer after second pass)

- using linac BPMs to measure trajectories, adjust combiner correctors to ensure on-axis beam
- adjust combiner delay to maximize $x(\phi)$ in spreader
- using spreader BPMs, adjust spreader correctors for proper launch into first FFAG cell

10 GeV pass

- adjust voltage of energy-compensating cavity to achieve nominal max energy
- deflect beam through detector bypass lines
- using BPMs at end of detector bypass line ensure proper launch back into FFAG

deceleration passes to dump

- adjust combiner delay to minimize $x(\phi)$ in spreader
- extract to low energy ring when appropriate
- deflect last pass to dump
- adjust energy-compensating cavity so that extracted beam energy is equal to injected beam energy (~ 10 MeV)

ramp up beam current

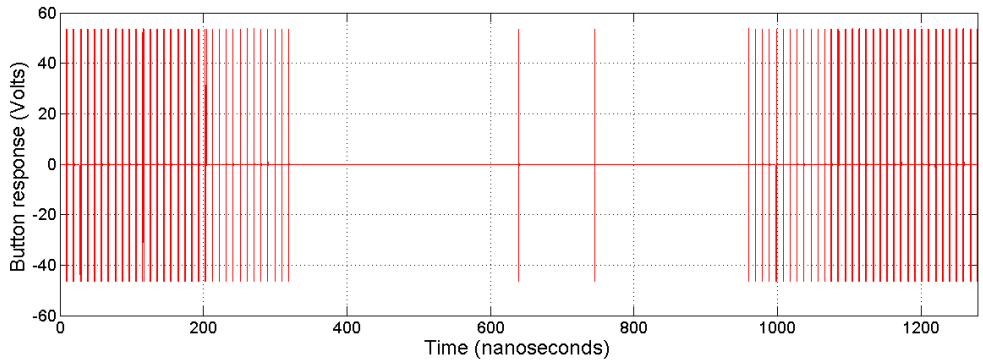
establish nominal pattern with nominal intensity bunches using an approach which minimizes transient beam loading in the linac:

- start adding additional accelerating bunches (incrementing by 1, spaced by 9.4 MHz until all trains have some bunches) every 11 RHIC revolution periods
- inject batches of 120 bunches at increasing rate to establish the complete periodic structure
- after linac transients decay, inject diagnostic bunches and continuously monitor and correct the orbit

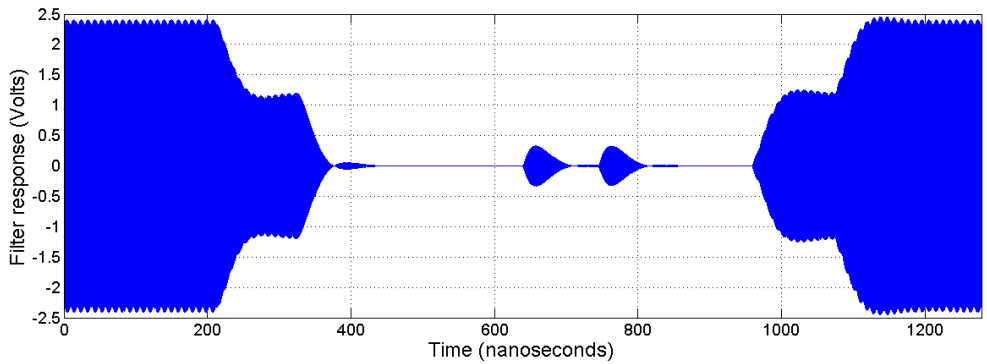
Routine monitoring

- the diagnostic bunches will be monitored continuously

Transformer signal



BPM response



- signals from bunch train decay well before diagnostic bunches

- measurements from button BPMs in the spreaders/combiners can time-resolve single-bunch measurements; the data can be delivered real-time and used to detect changes in beam conditions

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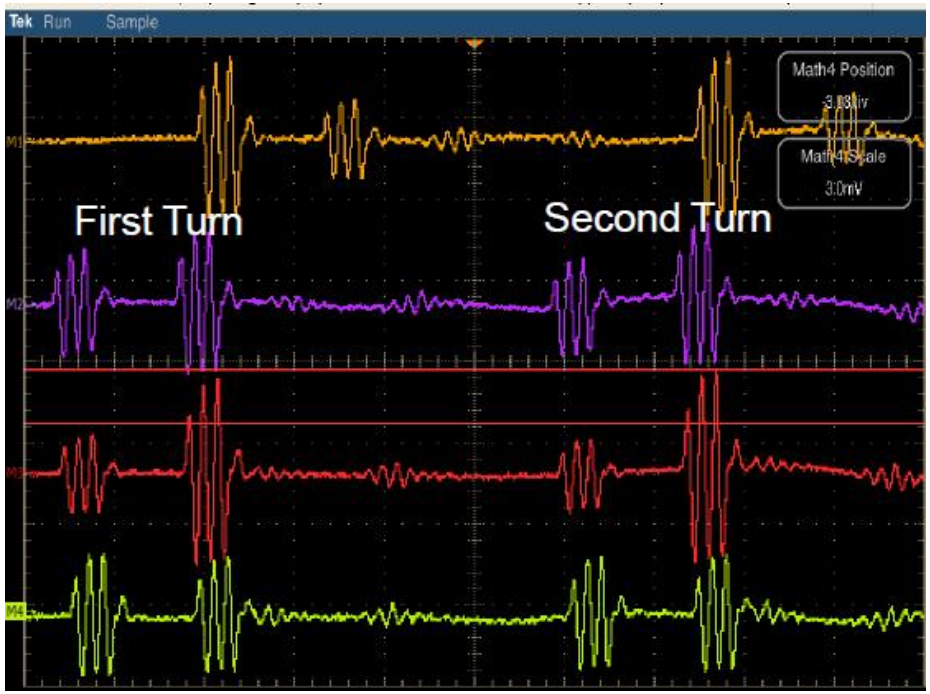
Fast Scope for Bunch-by-Bunch Monitoring

An (expensive) fast oscilloscope connected directly to a button BPM (e.g in the linac or FFAG cell) would be useful for monitoring bunch-by-bunch beam positions. Studies concerning survivability in a high radiation environment would be needed.

example from EMMA



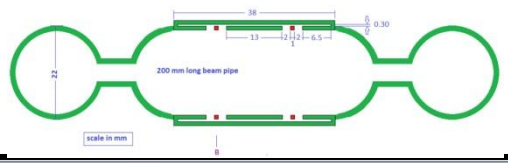
averaged signals from two (multiplexed) BPMs on fast sampling (20 GSPS?) scope

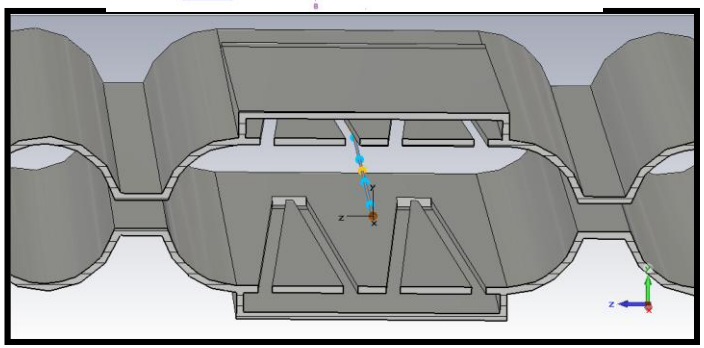
example scope

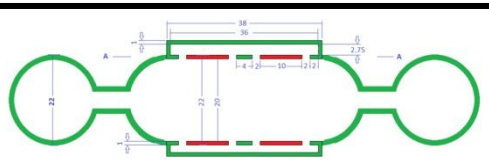
Lecroy: 4-channel, 40 GSPS, 20 GHz bandwidth (930SZi-A)

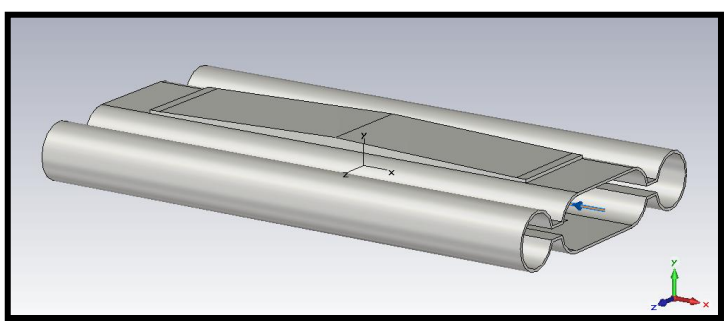
Bunch-by-Bunch BPM (P. Thieberger)

With fewer BPMs than magnets, the space between some FFAG magnets could be used entirely by a BPM; this design produces "stretched" output pulses (from 13 ps rms bunches) intrinsically in the BPM in-vacuum hardware

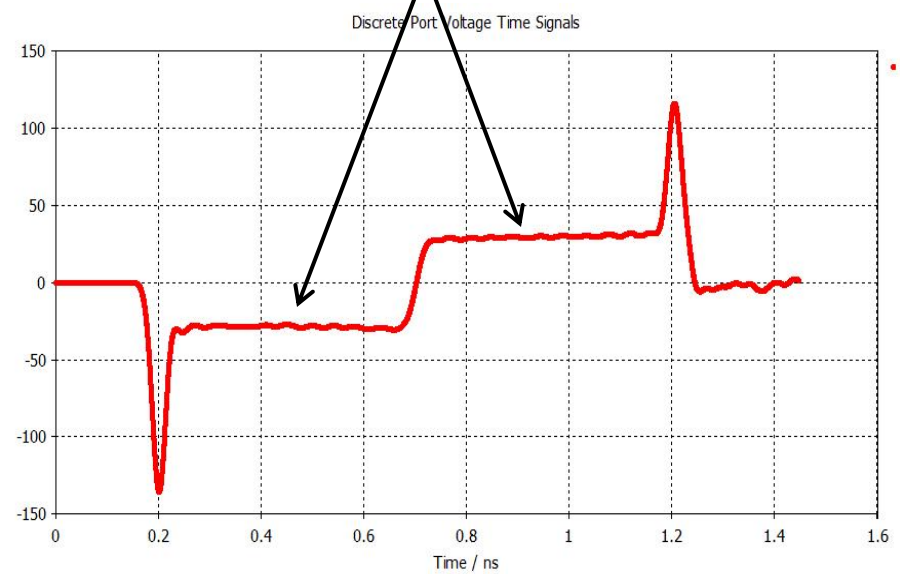








long sampling platforms



1.0 ns

1.21 ns = $\frac{1}{2}$ 413 MHz rf wavelength
= minimum FFAG bunch spacing

Summary

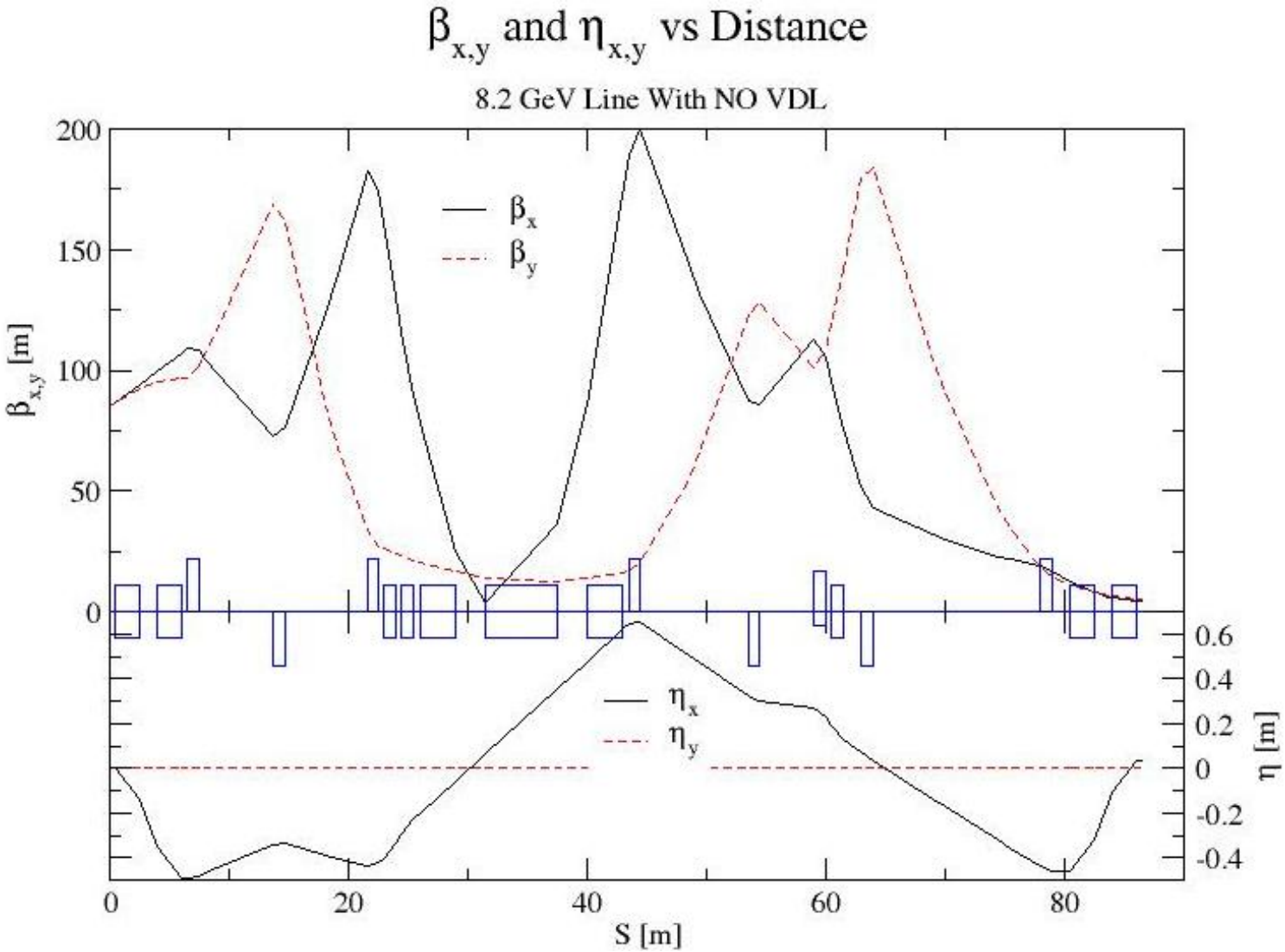
Instrumentation

- The filling scheme has a gap allowing for isolated bunches
- These bunches will be used for diagnostic purposes using conventional beam diagnostics (BPMs and imaging)
- The diagnostics presented are based on existing technologies with proven performance

Commissioning

- Commissioning planning has started

Backup Slides



$\Delta E/E$ = 2E-4, tolerance on linac energy gain (spin decoherence considerations)
η = 0.7 m, maximum dispersion for worst-case - highest energy
Δx = 140 μm, resultant change in beam position